Spaceborne Multiwavelength HSRL Aerosol Lidar (aka…Über lidar)

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Outline

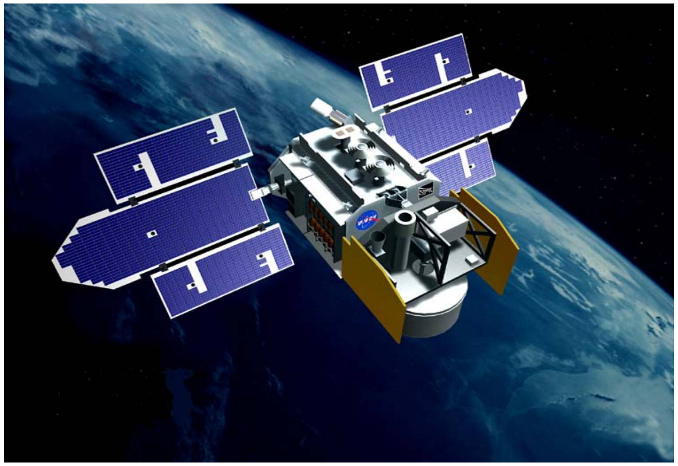
- Current capability of spaceborne aerosol lidars
- Backscatter lidar issues
- High Spectral Resolution Lidar (HSRL)
- Multiwavelength ("$3\beta+2\alpha$") Aerosol Retrievals
- Estimated spaceborne system parameters
- Recommended post-2010 satellite mission
- Summary

Current Capability: The Geoscience Laser Altimeter System (GLAS)

GLAS Observation Periods and Data Quality

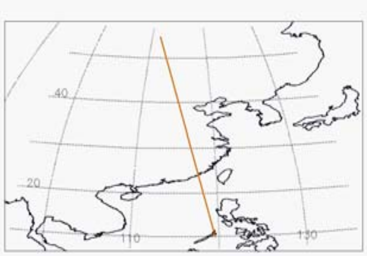
Date	Orbit Crossing Time (Local)	532 nm	1064 nm	Laser	Data Product Version
20Feb03 - 29Mar03	TBD	None	Excellent	1	13
25Sep03 - 18Nov03	20:17,08:17 - 18:58,06:58	Excellent	Excellent	2a	19
17Feb04 - 21Mar04	TBD	Excellent - Good	Excellent - Good	2b	22
18May04 - 21Jun04	TBD	Fair - Poor	Good - Fair	2c	NA
04Oct04 - 09Nov04	TBD	Fair - Poor	Excellent	3a	22
17Feb05 - 24Mar05	TBD	Fair - Poor	Excellent	3b	19
20May05 - 24Jun05	TBD	Fair - Poor	Excellent	3c	22
21Oct05 - 24Nov05	TBD	TBD	TBD	3d	22

Data Distribution:
http://nsidc.org/daac/icesat/
Product Information & Browse:
http://glo.gsfc.nasa.gov/

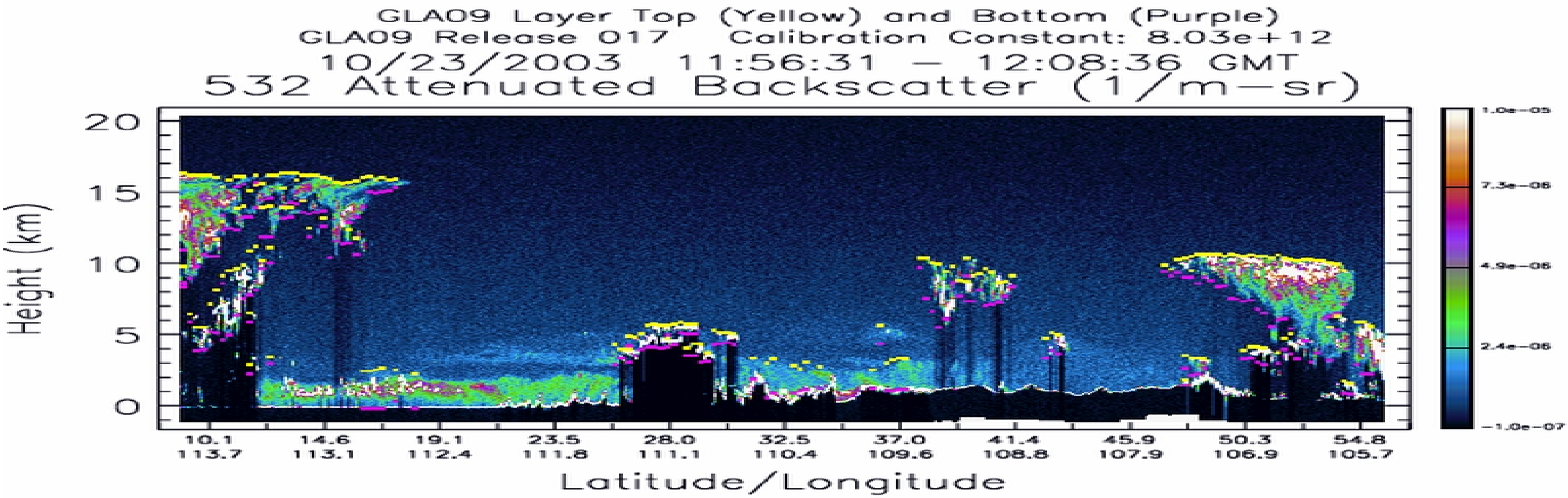


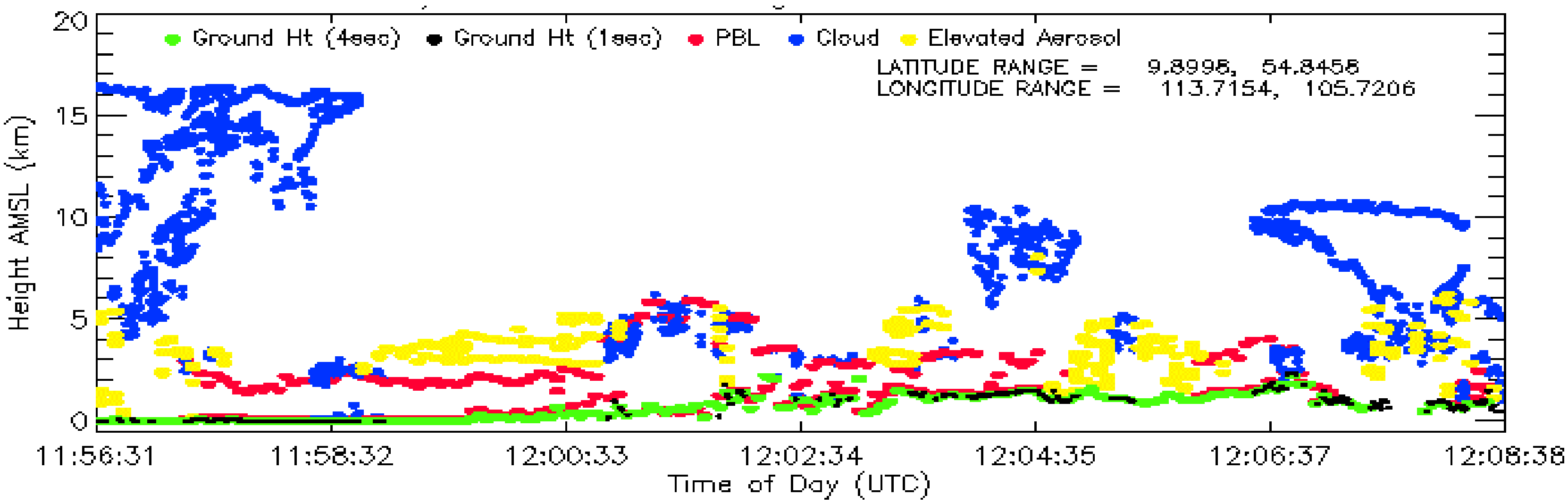
Wavelengths	532 nm	1064 nm
Detection Scheme	Photon Counting	Analog
Laser Pulse Energy	36 mJ	74 mJ
Laser PRF	40 Hz	40 Hz
Telescope Diameter	1.0 m	1.0 m
Receiver FOV	0.19 mrad	0.50 mrad
Optical Bandwidth	< 25 pm	< 1.4 nm
Detector Quantum Efficiency	0.7	0.3
Vertical Resolution	76.74 m	76.74 m
Surface Altimeter Digitizer Resolution		10 cm

Jim Spinhirne, NASA/GSFC



Observed Backscatter Cross Sections and Layer Heights from GLAS





Along Track Resolution: 40, 5 & 0.25 Hz (~175 m, 1.4 & 28.4 km) Jim Spinhirne, NASA/GSFC

Current Capability: CALIPSO + A-Train

Three co-aligned instruments:
– **CALIOP**

(3-channel lidar)
– 532 nm ||
– 532 nm ⊥
– 1064 nm

– **Imaging IR Radiometer**
– **Wide-Field Camera**

The A-train gives our first chance to routinely acquire aerosol profiles along with passive retrievals from a variety of techniques (MODIS, OMI, PARASOL)

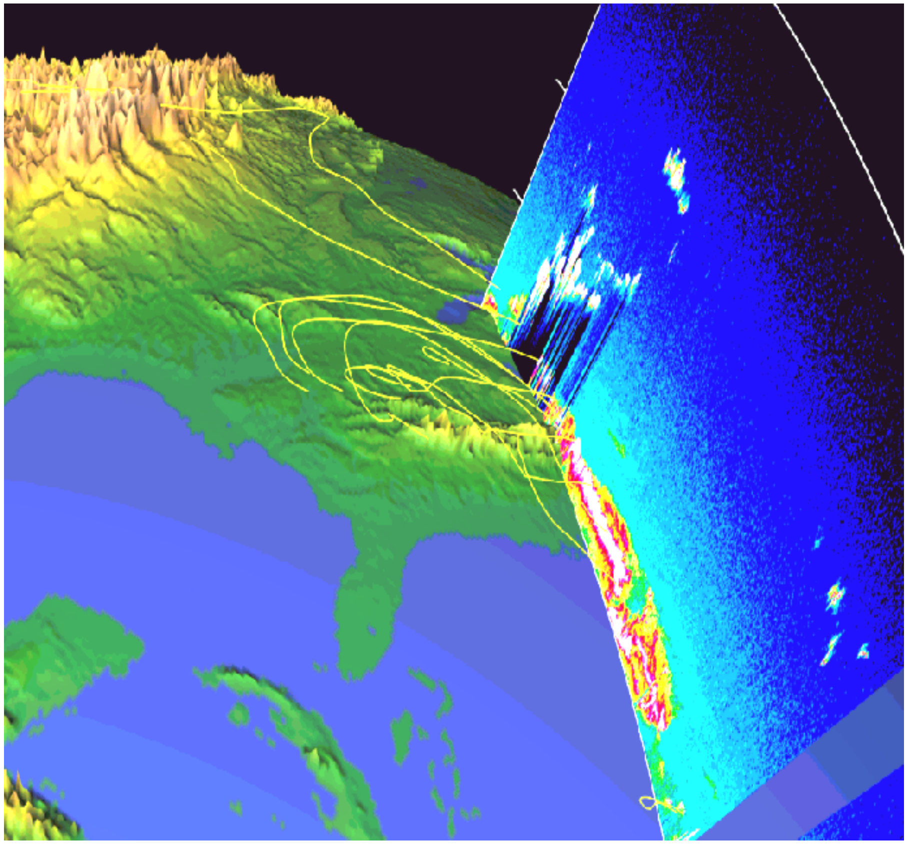
CALIOP also provides aerosol observations in new places: above clouds, in the polar regions.

Two spectral channels and polarization provide qualitative information on size, shape

Dave Winker, NASA/LaRC

CALIOP provides vertical distribution plus qualitative information on aerosol type

- CALIOP provides vertical distribution of aerosol
  - Layer heights via backscatter profiles
  - Extinction profiles via
    - Lidar inversion or
    - Constrained inversion using MODIS column information



- Using depolarization and color ratios, can tell when dominated by:
  - Coarse mode: sea salt, dust
    - depolarizing: dust
  - Or accumulation mode: smoke, industrial
    - adding OMI: discriminate weakly/strongly absorbing aerosol

- Altitude and back-trajectories to sources also give clues to composition

Dave Winker, NASA/LaRC

Backscatter Lidar Issues

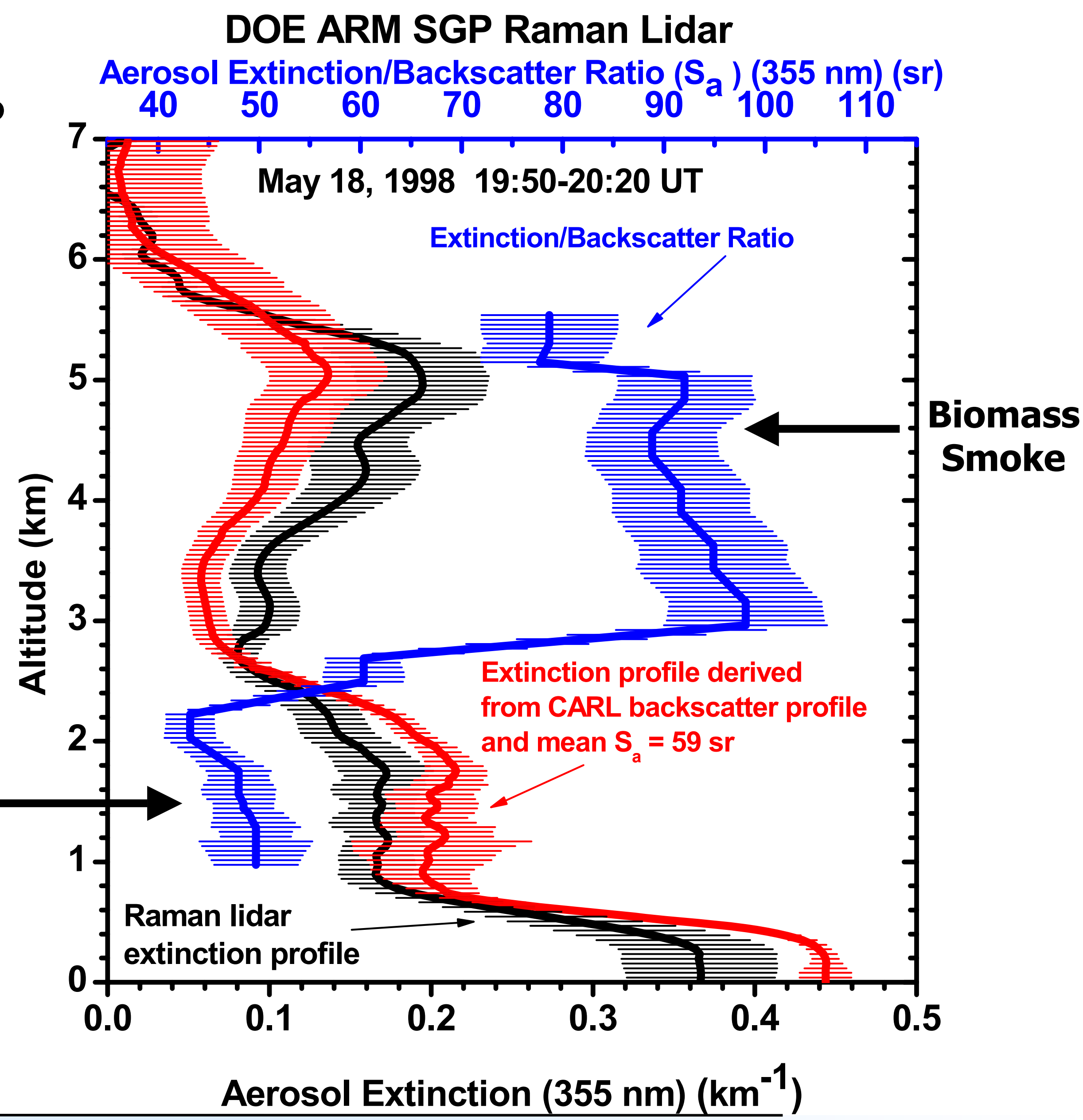
- Calibration
  - Must calibrate in some region assumed to be free of aerosols and clouds; CALIPSO calibrates at 30-34 km.
  - Can limit calibration to night only; calibration may drift during day

- Measures attenuated total backscatter
  - Retrieval of aerosol backscatter requires assumption of extinction-to-backscatter ratio S_a
    - Depends on aerosol composition, size, and shape
    - Varies over large range: $\sim 10 < S_a < \sim 110$
    - Assumed value based on inference of aerosol type

Extinction-to-backscatter ratio variability

- Multiyear Raman lidar measurements over DOE ARM SGP site found large variations in vertical profile of S_a occurred 30% of time
- Significant variability in particle size, composition, and/or shape often occurs
- Uncertainty in profile of S_a raises potential for structural error in backscatter lidar retrieval

(Ferrare et al.,JGR, 2000)

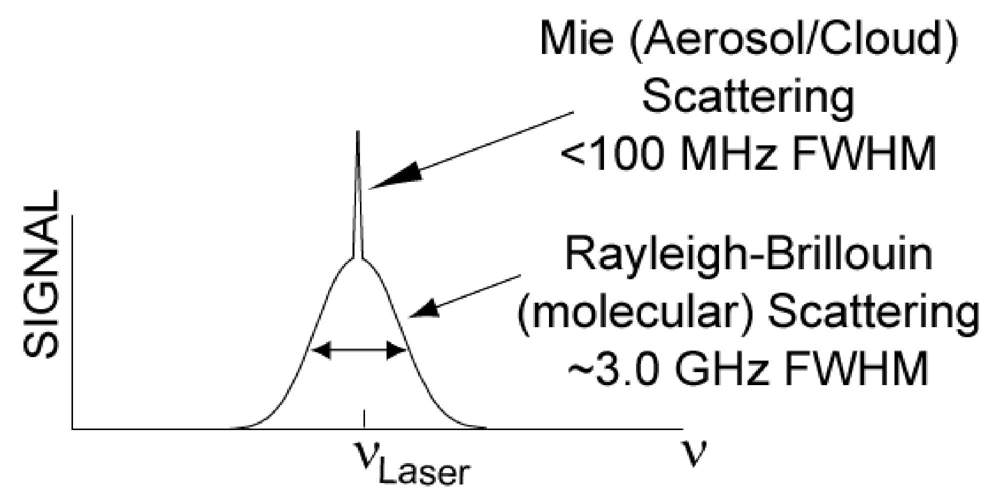


High Spectral Resolution Lidar (HSRL)

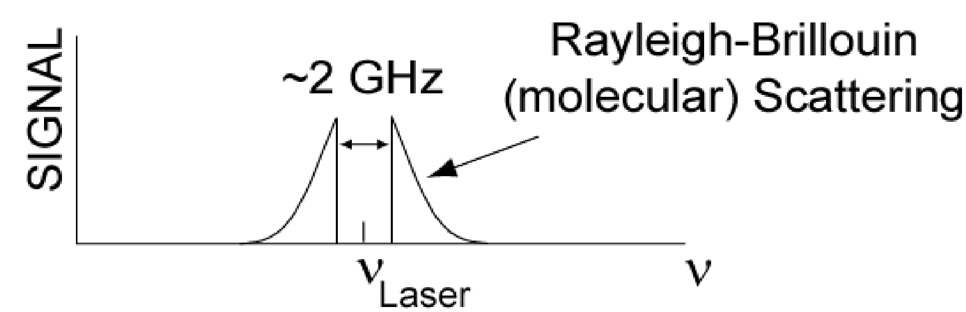
HSRL relies on spectral separation of aerosol and molecular backscatter in lidar receiver.

- **HSRL independently measures aerosol and molecular backscatter**
  - Can be internally calibrated
  - No correction for extinction required to derive backscatter profiles
  - More accurate aerosol layer top/base heights
- **HSRL enables independent estimates of aerosol backscatter and extinction**
  - Extinction and backscatter estimates require no S_a assumptions
  - Provide *intensive* optical data from which to infer aerosol type
  - Measurements of extinction at 2 wavelengths and backscatter at 3 wavelengths enables retrieval of aerosol microphysical parameters and concentration

Atmospheric Scattering



Effect of Iodine Vapor Notch Filter



HSRL: 2 equations, 2 unknowns

Measured Signal on Molecular Scatter (MS) Channel:

$$P_{MS}(r) = \frac{C_{MS}}{r^2} F(r)\,\beta_m(r)\,\exp\left\{-2\int_0^r \left[\sigma_m(r') + \underline{\sigma_p(r')}\right] dr'\right\}$$

Particulate Extinction

Measured Signal on Total Scatter (TS) Channel:

$$P_{TS}(r) = \frac{C_{TS}}{r^2}\left[\beta_m(r) + \underline{\beta_p(r)}\right]\exp\left\{-2\int_0^r \left[\sigma_m(r') + \sigma_p(r')\right] dr'\right\}$$

$$\frac{\sigma_p(r)}{\beta_p(r)} = \underline{S_p}$$

Ext/Backscatter

Particulate Backscatter

Retrieved Parameters

Heritage and Future Prospects

U. Wisc.- Eloranta 1977 – …	Operating ground-based systems for decades; first etalon-based system; first 532 nm iodine vapor filter system;
Colo. St. - She 1983 – 1998	First vapor filter systems, various wavelengths; first demonstration of temperature measurements
NIES - Liu 1997 – 2001	Ground-based system; 532 nm iodine vapor filter technique
DLR 1998 – 2000	First practical aircraft-based system (no longer functional); 532 nm using iodine vapor filter technique
LaRC 2004 – …	Developed aircraft-based system 532 nm HSRL (iodine filter), 1064 backscatter, and depolarization at both wavelengths. Funded to 355 nm HSRL channels through IIP (to be completed by 2008).
CNES 2005 ? – …	“LNG” -- Leandre upgrade; 355 nm HSRL (Mach Zehnder), 1064 backscatter
ATLID/Earthcare 2012 – …	Spaceborne system; etalon-based receiver; 355 nm

Next Step: “3β+2α” HSRL retrievals

- Fundamental data products
  - Backscatter at 3 wavelengths (3β) : 355, 532, 1064 nm
  - Extinction at 2 wavelengths (2α) : 355, 532 nm
  - Depolarization at 355, 532, and 1064 (dust and contrails/cirrus applications)
- Retrieved, layer-resolved, aerosol microphysical/macrophysical parameters (Müller et al., 1999, 2000, 2001; Veselovskii et al.,2002,2004)
  - Effective and mean particle radius (errors < 30-50%)
  - Concentration (volume, surface) (errors < 50%)
  - Complex index of refraction
    - real (±0.05 to 0.1)
    - imaginary (order of magnitude if < 0.01; <50% if > 0.01)
  - Single scatter albedo (±0.05; error increases for $r_{eff} > 0.3\ \mu m$)
- Microphysical retrieval issues
  - Constraining assumptions: positivity, smoothness of size distribution, consistency between retrieved parameters and input optical data
  - Assumes wavelength independent and size independent refractive index
  - Assumes spherical particles; upgrade to spheroids is planned
  - Retrieval is restricted to particle radii > 50 nm
  - Not operational: requires extensive computation time and expert operator, software package in alpha version has been developed for more general use

Lidar Data Product Wish List

Backscatter Lidar

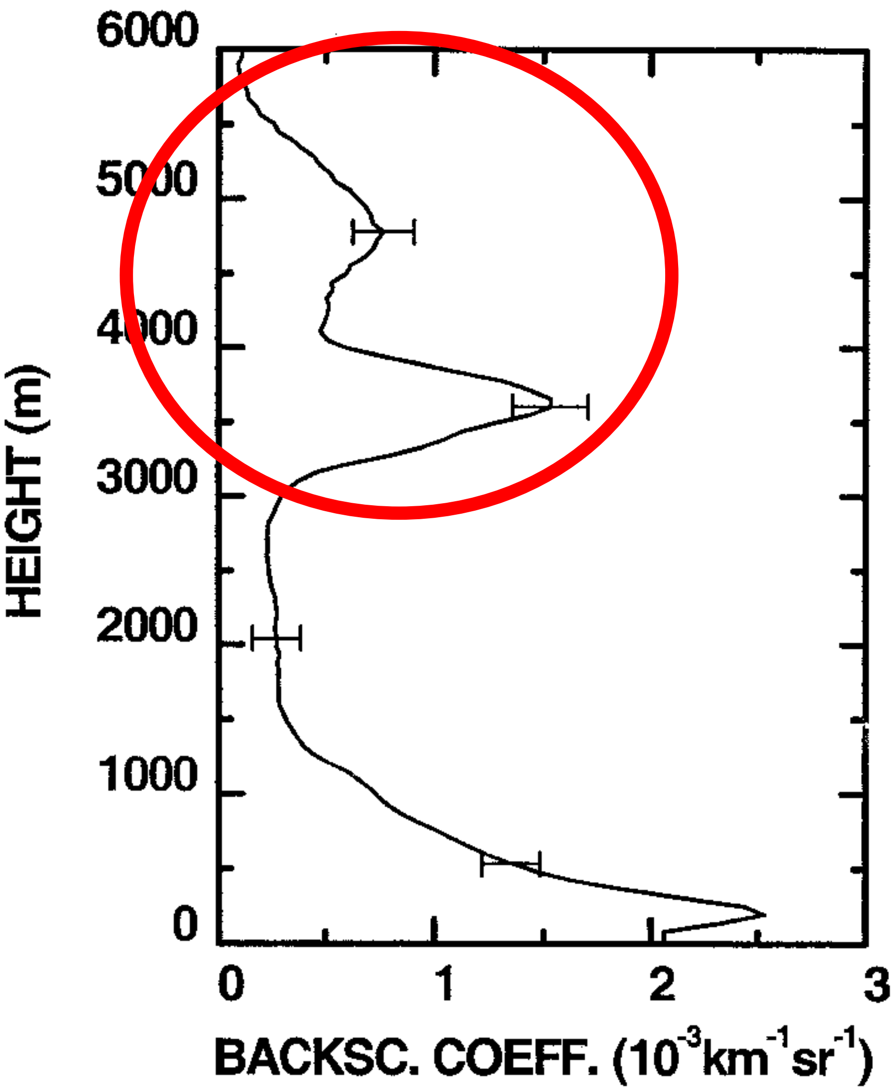
Backscatter Lidar + Passive

3β+2α Advanced HSRL

- Aerosol layer heights
- Qualitative vertical distribution (backscatter profile)
- Aerosol type vs. altitude
- Extinction profile from backscatter
- Extinction profile with column constraint
- Fine-coarse mode fraction vs. altitude
- Extinction profile
- Complex refractive index vs. altitude
- Aerosol size vs. altitude
- SSA vs. altitude
- Concentration vs. altitude

Further enhanced by addition of passive sensors

Example microphysical retrieval #1



- From Müller et al., Appl. Opt., 2001
- Data from LACE 98 campaign over Lindenberg, Germany
- Microphysical retrieval performed for upper layer (3-6 km) and compared to in situ aircraft measurements

Ex. #1- Müller et al. (2001) case study using 3-backsatter and 2-extinction wavelengths

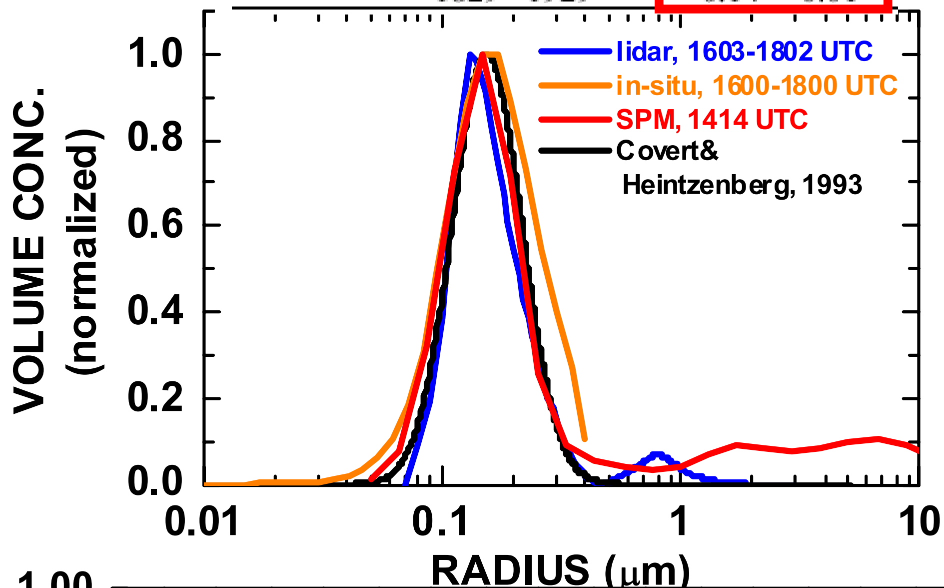
Retrieval results compared to in situ measurements for biomass plume.

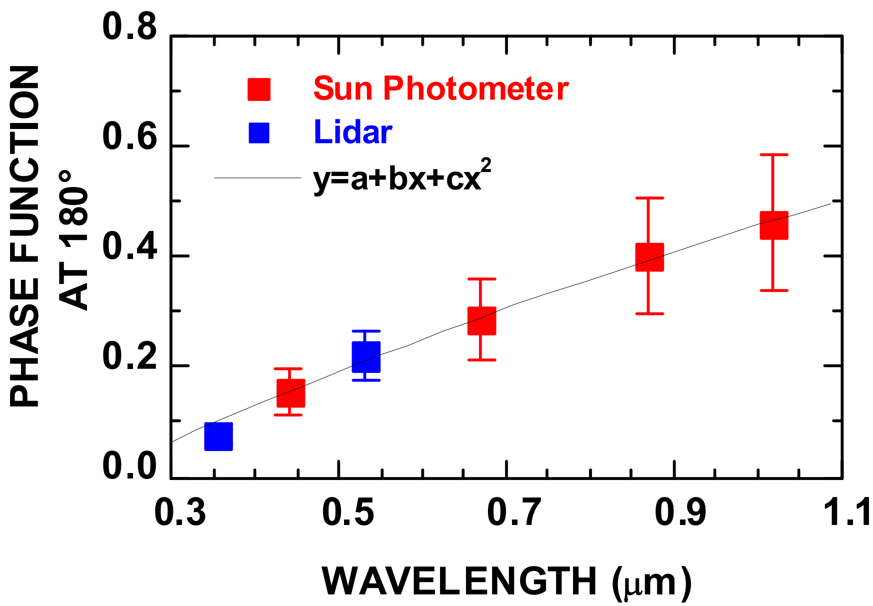
Parameter	Lidar Retrieval	Aircraft, in situ	
		r>1.5 nm	r>50 nm
r_{eff}, µm	0.27 ±0.04	0.24±0.06	0.25±0.07
Number concentration, cm^{-3}	305±120	640±174	271±74
Surface concentration, $\mu m^2 cm^{-3}$	145±8	110±50	95±55
Volume concentration, $\mu m^3 cm^{-3}$	13±3	9±5	8±5
m_R	1.63±0.09	1.56	1.56
m_I	0.048±0.017	0.07	0.07
SSA (532 nm)	0.81±0.03	0.78±0.02	0.79±0.02
SSA (355 nm)	0.76±0.06	–	–
S_a (532 nm) sr^{-1}	73±4 (75)	–	–
S_a (355 nm) sr^{-1}	51±4 (45)	–	–

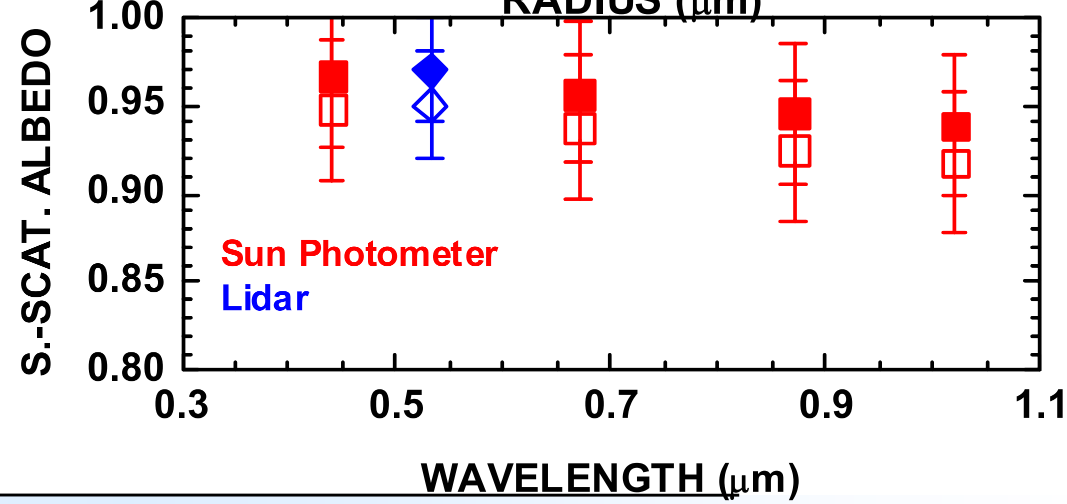
Example microphysical retrieval #2

- Mixture of urban and Arctic haze
- Leipzig, Germany during April 2002
- Comparison of retrievals and measurements
  - Lidar (3β + 2α) retrieval
  - AERONET Sun photometer sun and sky radiance retrieval (Dubovik et al., 2000)
  - In situ measurements
- Müller, Dubovik et al., JGR, 2004

	Time, UTC	r_{eff}, µm
SPM	1415	0.18 ± 0.05
	1616	0.22 ± 0.06
Lidar	1603 – 1802	0.18 ± 0.02
	1823 – 1922	0.19 ± 0.04
In Situ	1600 – 1800	0.14 ± 0.03
	1829 – 1929	0.14 ± 0.01







Spaceborne 3β+2α HSRL

	CALIPSO	Spaceborne 3β+2α HSRL (rough estimates)
Telescope Diameter	1.0 m	1.5 m
Fundamental Resolution	30 – 60 m vertical, 333 m horizontal	30 m vertical, 70 m horizontal
Backscatter Resolution	120 m vertical, 40 km horizontal	120 m vertical, 20 km horizontal (10% error)
Extinction Resolution	(Indirect) 120 m vertical, 40 km horizontal	(Direct) 900 m vertical, 20 km horizontal (15% error)
Power	200 W @ 700 km	400 W @ 400 km, 825 W at 640 km
Mass	172 kg	265 - 325 kg

Technology maturity: transmitter

- In general, higher average power is required for HSRL technique over current backscatter lidars (e.g., 3x-5x over CALIPSO, GLAS)
  - Injection-seeded Nd:YAG laser capable of up to 50 W can be built using current technology
  - Space qualified seed lasers are currently available
  - Required spectral purity and frequency agility have been demonstrated
  - Power levels can be achieved with existing pumping architectures
  - High power levels will drive up cost of spacecraft bus
- Frequency doubling to 532 nm has been demonstrated
  - Lifetime tests on CALIPSO test laser are very positive
- Frequency tripling to 355 nm must be assessed
  - Damage due to contamination poses greater problems in UV.
  - Not clear that contamination control procedures developed for 532-1064 systems will be adequate at 355
  - Lab work needed to evaluate contamination control procedures

Technology maturity: receiver

- Iodine absorption cell
  - Used on ground-based systems for many years
  - Alignment insensitive
  - Achieves excellent suppression of Mie backscatter in “molecular channel”
  - Poses no technical problem for space

- Multiple Fabry Perot interferometer
  - Demonstrated in the 1970s (Eloranta)
  - No existing systems employ this technique
  - Systematic errors associated with spectral characterization of etalon passbands may be an issue (incomplete suppression of Mie backscatter requires careful calibration of etalon frequency response)

- Mach Zehnder interferometer
  - Demonstrated for ground-based wind application
  - Not yet demonstrated for HSRL
  - CNES developing Mach Zehnder system for Leandre upgrade
  - May have a problem with excessive noise from daytime background

Recommended post-2010 satellite mission

As envisioned in PARAGON (Progressive Aerosol Retrieval and Assimilation Global Observing Network) initiative (Diner, Kahn, Ackerman, Seinfeld, BAMS, October 2004):

Mission concept	Core Instruments	NASA Center
Aerosol Global Interactions Satellite (AEGIS) (Diner et al.)	Multiangle SpectroPolarimetric Imager (MSPI) High Spectral Resolution Lidar (HSRL)	JPL/GISS/GSFC LaRC
3-D Cloud-Aerosol Interaction Mission (CLAIM-3D) (Martins et al.)	Cloud Scanner System (CSS) (Cloud side scanner + rainbow camera)	GSFC/GISS

Principal focus on aerosol-cloud interactions, including climate forcing and impact on hydrological cycle

- To extrapolate aircraft CCN particle samplers and CCN-cloud activation models, data are acquired with adequate vertical and horizontal resolution to link localized information to the global scale, with capability to correlate cloud properties with aerosol loading, distribution, and composition.

Additional focus on key, vertically-resolved measurements for particulate air quality and aerosol direct radiative forcing

AEGIS/CLAIM-3D measurements

MSPI (“Über-MISR”)	• **Column-averaged optical, microphysical, and macrophysical aerosol properties**, including AOD, particle size distribution, SSA, real refractive index, and particle shape • **Layer-top heights** for distinctive aerosol plumes and effective height of absorbing aerosols • **Radiative “closure” between aerosol and cloud properties** and hemispherically-reflected top-of-atmosphere radiation • Interpolation and extrapolation of data from surface and suborbital sensors and the HSRL • **Improved aerosol characterization over water** relative to single-angle instruments by **taking advantage of sunglint** and coupling water-leaving radiance and aerosol retrieval over the entire spectral range
HSRL	• **Vertical profiles of aerosol backscatter and extinction** even for dispersed aerosol layers • **Layer-wise estimates of optical, microphysical, and macrophysical properties** (e.g., number/surface/volume concentrations, effective radius, complex index of refraction) • **Discrimination of aerosol particle shape and cloud liquid/ice phase** • **Ability to sense and characterize multiple layers**, including aerosols above clouds, below optically thin clouds, and in the stratosphere
CSS	• At cloud sides: **vertical profile of droplet effective radius and vertical profile of thermodynamic phase** • At cloud top: **cloud top temperature, cloud fraction, cloud optical depth, droplet effective radius, cloud top thermodynamic phase and cloud height** • **Cloud top evolution** over 3 to 6 minutes • **Comprehensive cloud droplet size distribution** including width of the size distribution

Summary

- Backscatter Lidar
  - Measures aerosol layer heights and thickness
  - Uncertainties due to relating aerosol backscatter and extinction
- HSRL
  - Unambiguous measurement of extinction and backscatter
  - Information on aerosol type through extinction-to-backscatter ratio (and other intensive observables)
- Multiwavelength ($3\beta + 2\alpha$) retrievals
  - Possible to implement 2-extinction, 3-backscatter wavelength system for retrieval of microphysical properties and concentration
  - Only known demonstrated remote sensing method for obtaining vertically resolved information on aerosol microphysical properties
- Potential future spaceborne system
  - Global, vertically (HSRL) and horizontally (MSPI) resolved measurements of aerosol optical and microphysical properties
  - Derive cloud properties (size, phase, drop size, optical depth) (CSS) and investigate aerosol-cloud interactions (HSRL, MSPI, CSS)